EP-DT
Detector Technologies

CERN strategies to reduce GHG emissions in particle detection at the LHC experiments

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on behalf of the CERN Gas Team

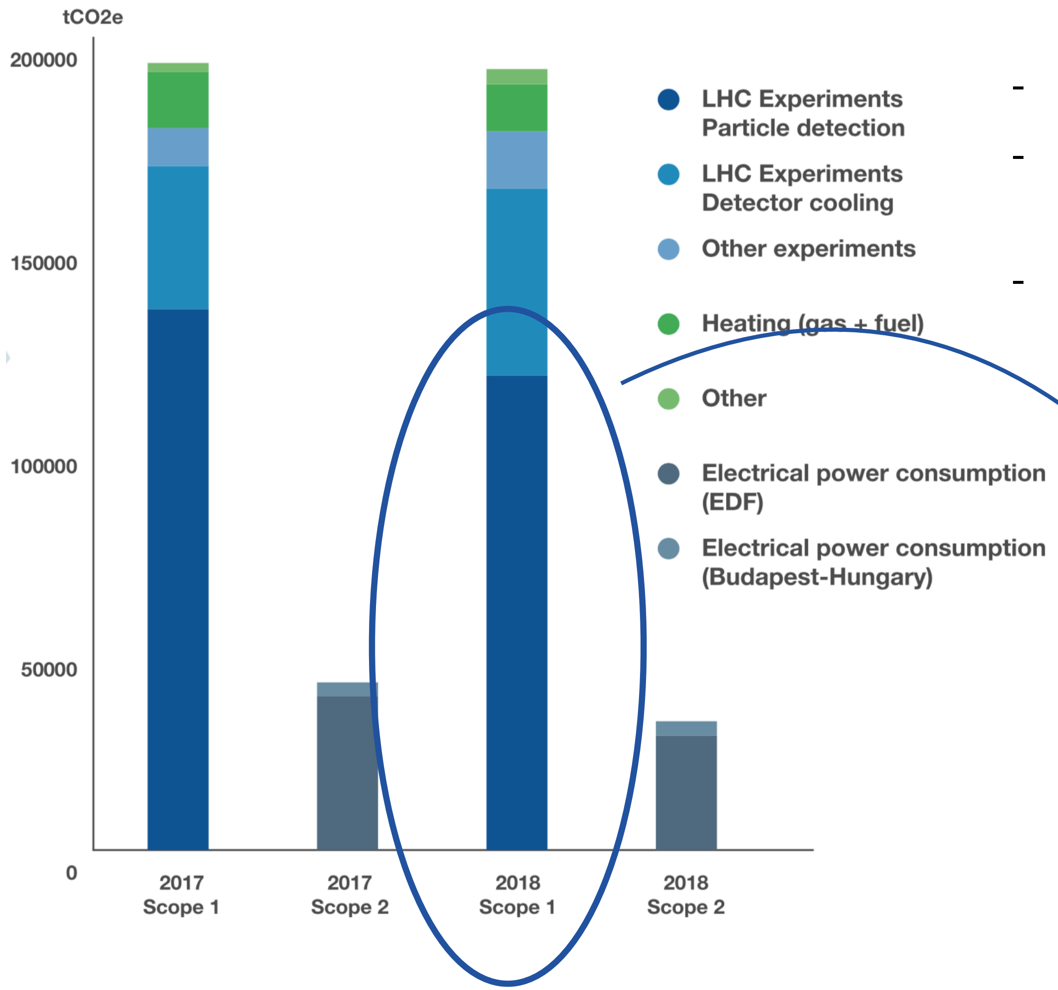
CERN

Workshop on Carbon Emissions at Future Facilities

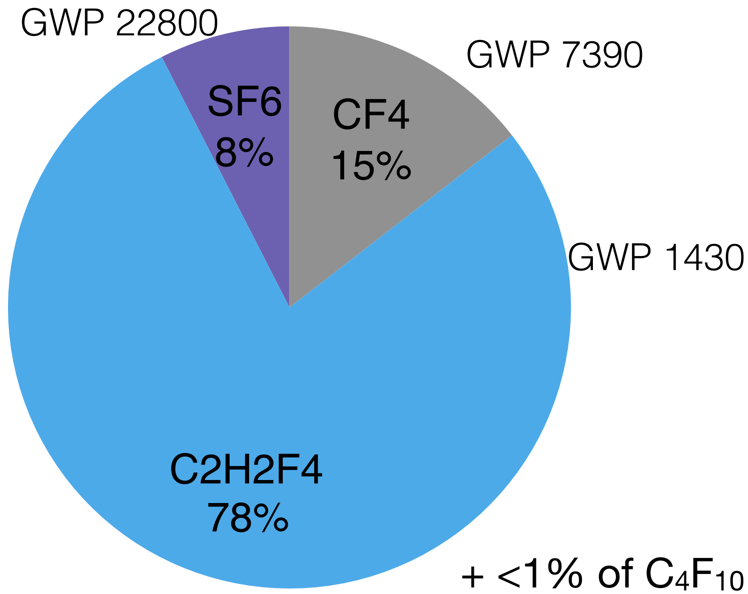
CERN, 9 November 2021

CERN commitment to reduce GHG emissions

Greenhouse gas emissions at CERN arise from the operation of the Laboratory's research facilities.
With climate change a growing concern, the Organization is committed to reducing its direct greenhouse gas emissions.



- 192.000 tCO_{2e} in 2018
- 92% of emissions related to large LHC experiments
- Most emissions from particle detection

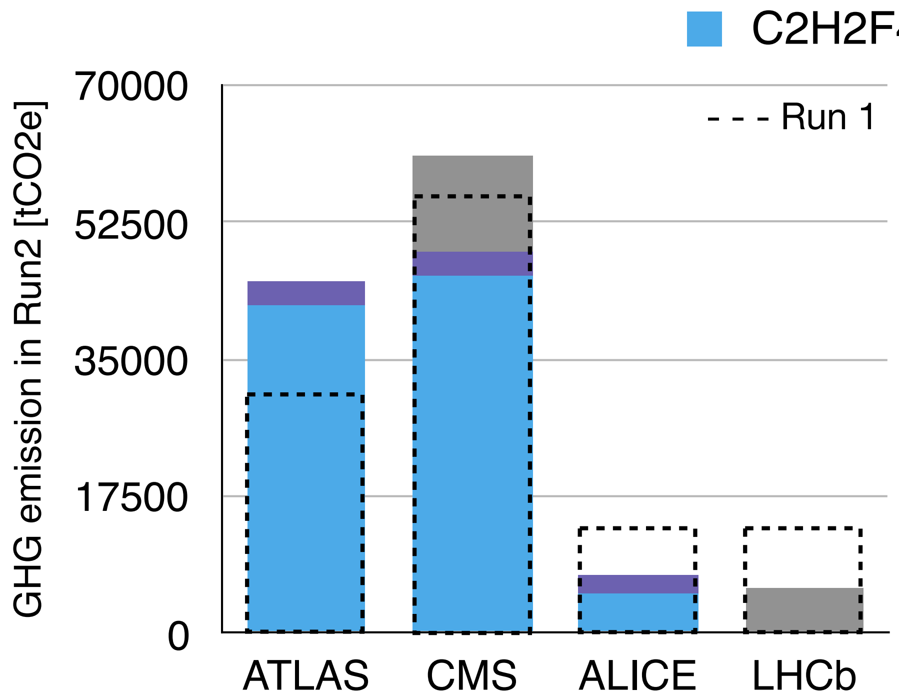


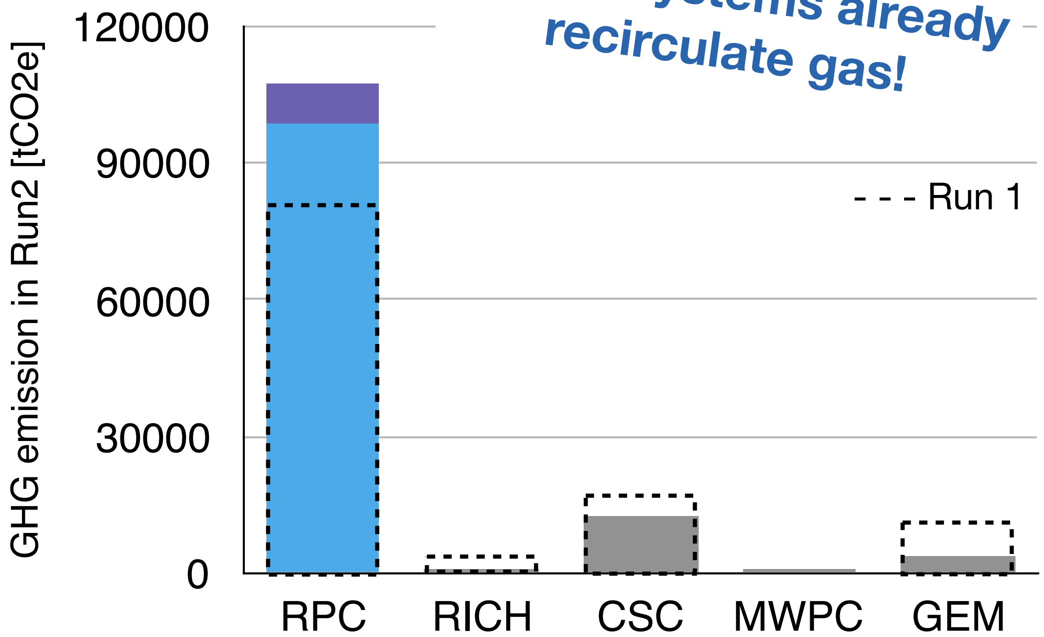
+ <1% of C_4F_{10}

https://e-publishing.cern.ch/index.php/CERN_Environment_Report/index

GHGs for particle detection at LHC: Run 2

GHGs are used in CERN experiments due to their properties necessary for good detector operation





All gas systems already recirculate gas!

Leaks in detectors
(ATLAS and CMS)

Leaks are concentrated in the gas inlets, polycarbonate gas connectors and Polyethylene pipes

Big leak search campaign on-going in LS2: fundamental to have access to chambers for repairing

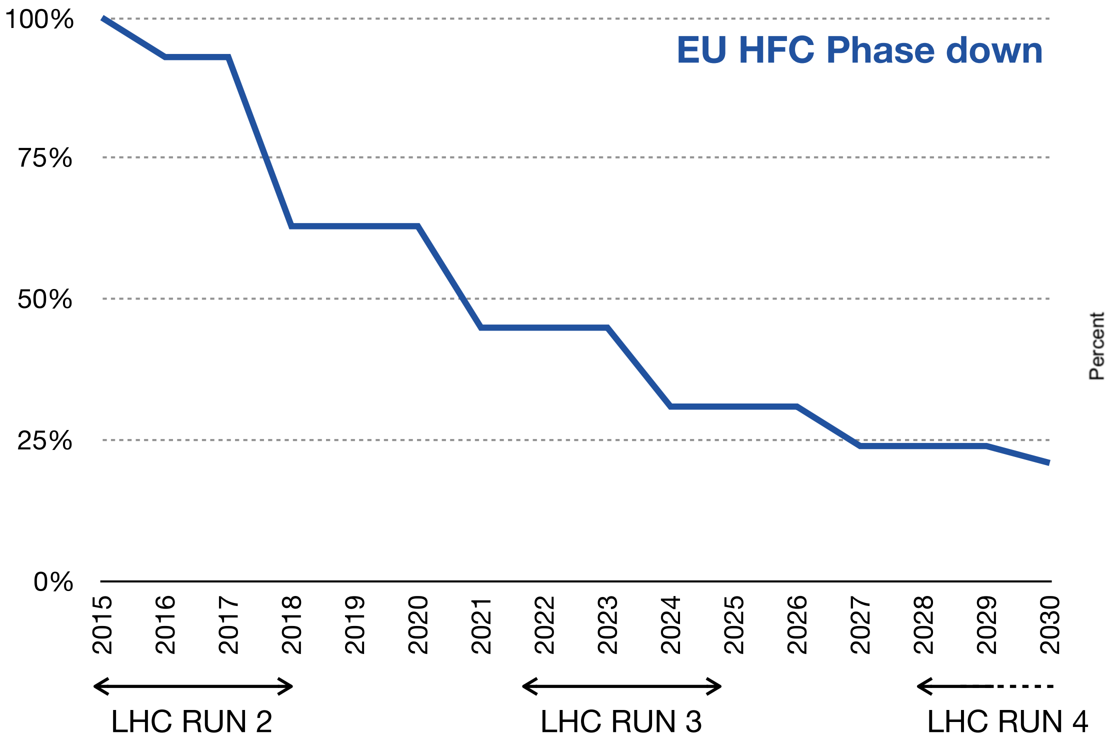
Permeation to Air
(CMS)

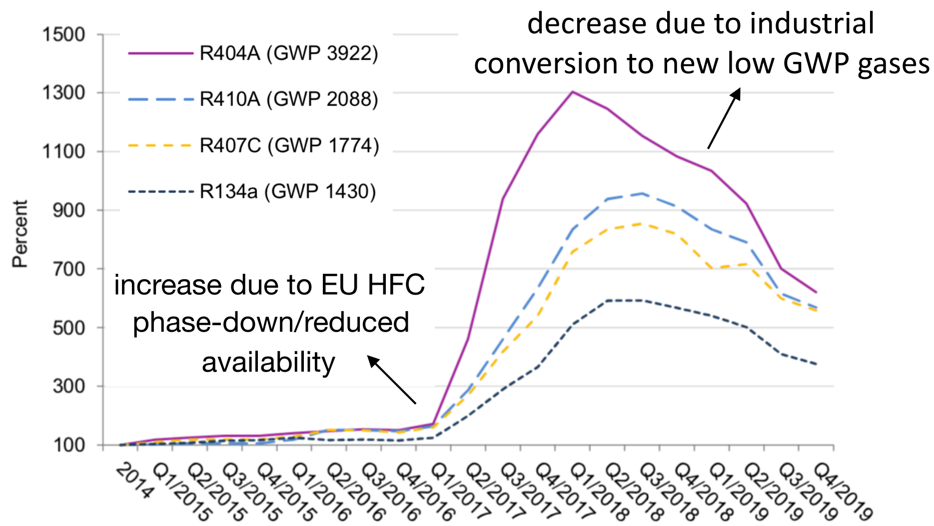
Upgrade to gas recirculation
(LHCb)

EU HFC phase-down policy

European Union "F-gas regulation":

- **Limiting the total amount** of the most important F-gases that can be sold in the EU from 2015 onwards and phasing them down in steps to one-fifth of 2014 sales in 2030.
- **Banning the use** of F-gases in many new types of equipment where less harmful alternatives are widely available.
- **Preventing emissions** of F-gases from existing equipment by requiring checks, proper servicing and recovery of the gases at the end of the equipment's life.





European Environment Agency, Fluorinated greenhouse gases 2019 report
Öko Recherche report, March 2020 J. Kleinschmidt et al.

Prices could increase in EU and availability in the future is not known.
Reduction of the use of F-gases is fundamental for future particle detector applications

CERN strategies for GHG reduction

CERN Strategies to reduce GHG emissions in particle detection

- **Optimization of current technologies**
  - Gas Recirculation
  - Particular attention to operation
  - Improved control and monitoring
- **Gas Recuperation**
  - Pressure swing
  - Membrane separation
  - Cryogenic/cold separation
- **Alternative Gases**
  - To $C_2H_2F_4$
  - To SF_6
  - To CF_4
- **Gas Disposal**
  - GHG destruction

Short-term

Long-term

Set aside

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Gas recirculation

Thanks to gas recirculation GHG emission already reduced by > 90% with respect to open mode systems!!!

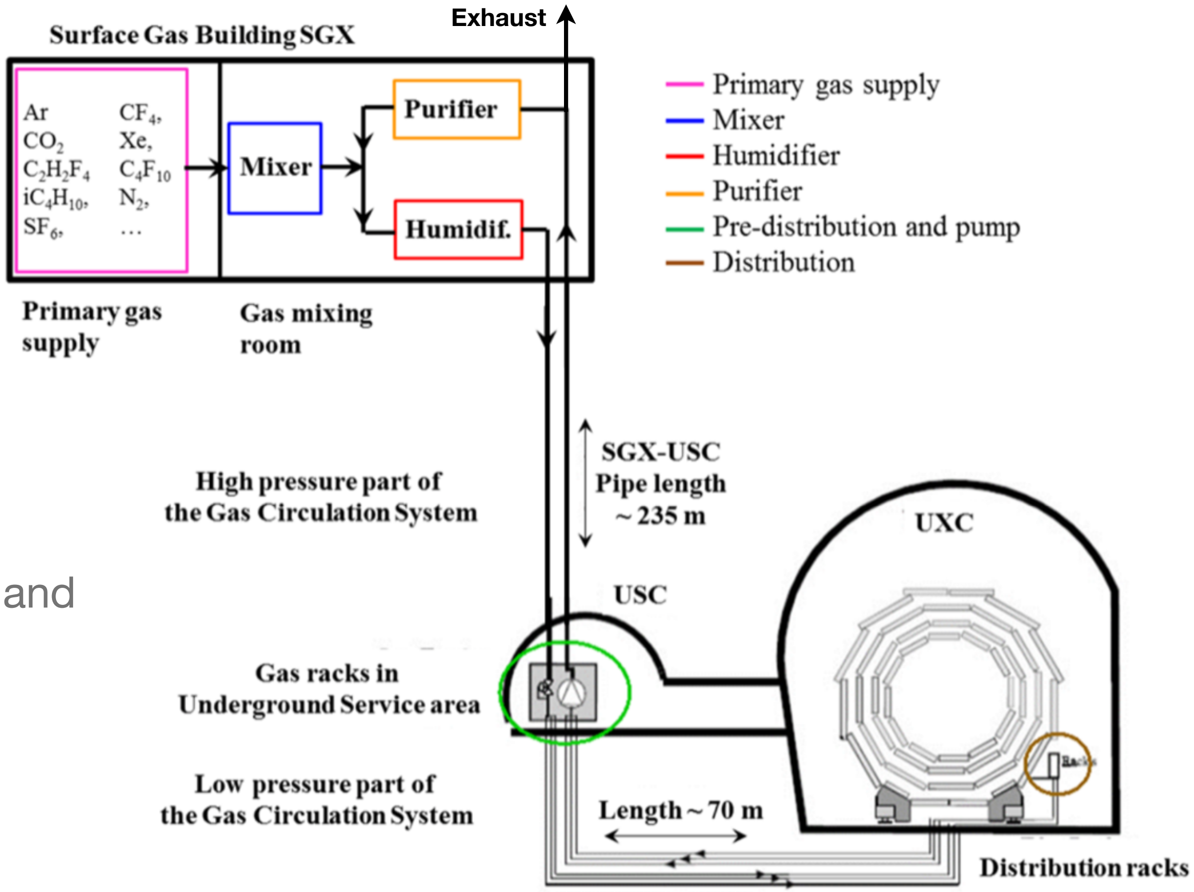
Detector volumes at LHC range from few to hundreds m^3

Advantages

- Reduction of gas consumption

Disadvantages

- Complexity in operation
  - Pressure and flow fluctuations, etc.
- Creation of impurities
  - Especially when F-gases present
  - Accumulation in the gas mixture, concentration depends on luminosity and recirculation fraction
  - They could affect long-term detector operation
- Gas purifying techniques
  - Needed to absorb impurities

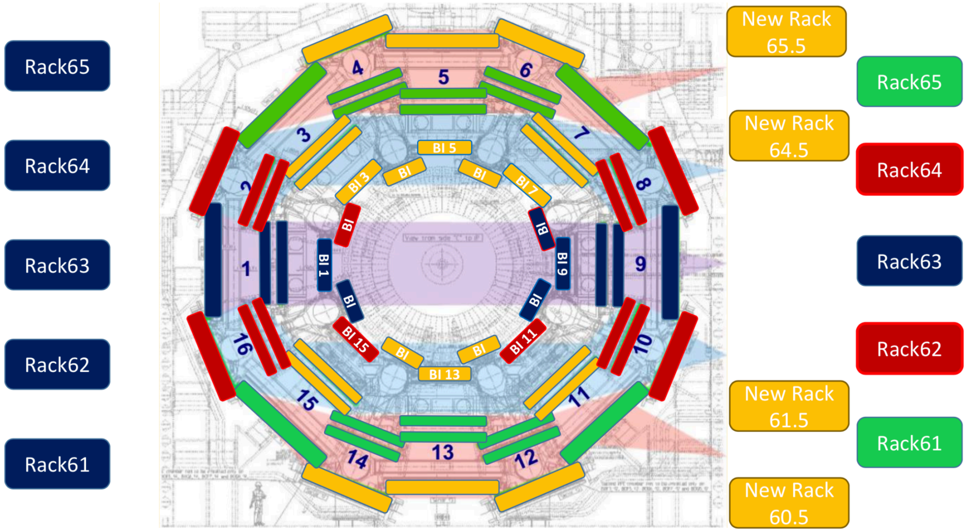


Minimization of flow/pressure fluctuations

Goal: to minimize the hydrostatic pressure on the detectors

- The RPC gas mixture has a high hydrostatic pressure: ~0.3 mbar/m
- The gas distribution racks are located in the cavern on different levels
  - The addition of new distribution racks will allow a better pressure equalisation between the chambers

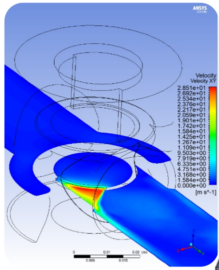
ATLAS RPC

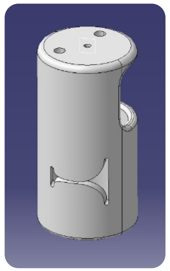


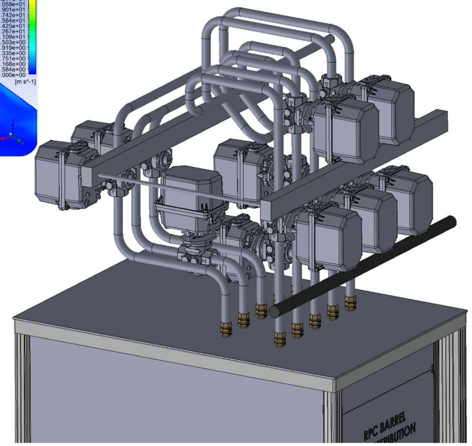
Goal: to minimize any chamber pressure/flow fluctuations from some 0.1 to ~ 0.1 mbar

- New automated regulation valves on the return of each distribution rack to minimize any pressure changes
  - To decrease the risk of developing new leaks at the detector level
- Installation of reference volumes
  - To have a good reference for the regulation of the detectors pressure
- Addition of gas impedances
  - To smooth pressure and flow fluctuations at the output of distribution system, i.e. pressure and flow seen by the detectors

CMS RPC







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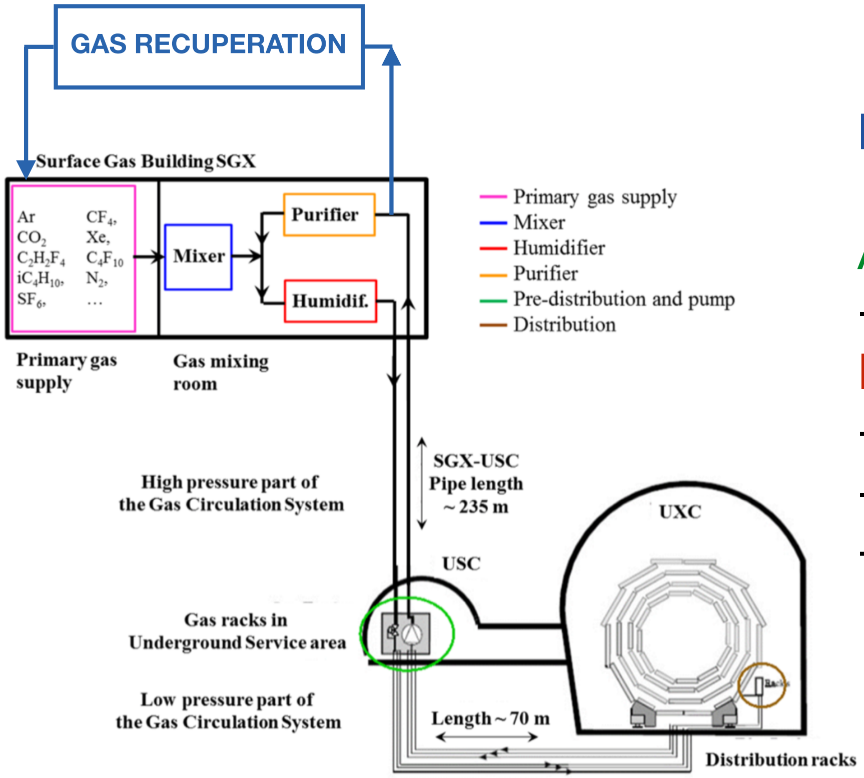
Gas Recuperation systems at LHC experiments

- Sometimes it is not possible to recirculate 100% of the gas mixture and a fraction cannot be re-used and therefore it would have bene sent to atmosphere
  - Detector permeability, detector requirements (max recirculation fraction tested), impurities, etc.
  - To keep lower N_2 concentration
- This fraction of gas mixture is sent to a recuperation plant where the most valuable component is extracted, stored and re-used
  - Often challenging to extract a single component
  - The quality of recuperated gas is fundamental



Many LHC gas systems with gas recuperation

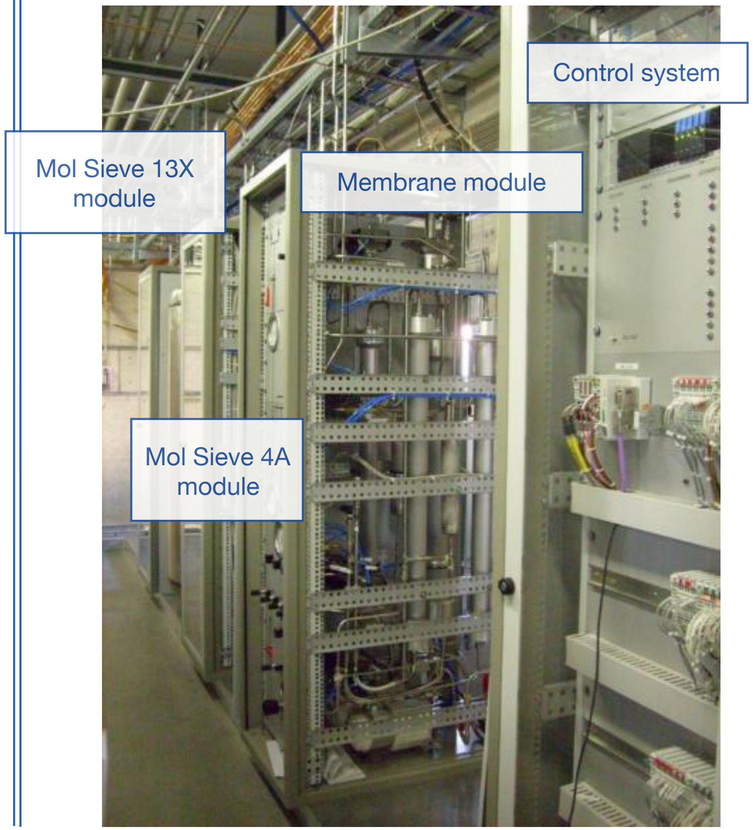
Advantages:
- further reduction of gas consumption

Disadvantages:
- higher level of complexity
- dedicated R&D
- gas mixture monitoring

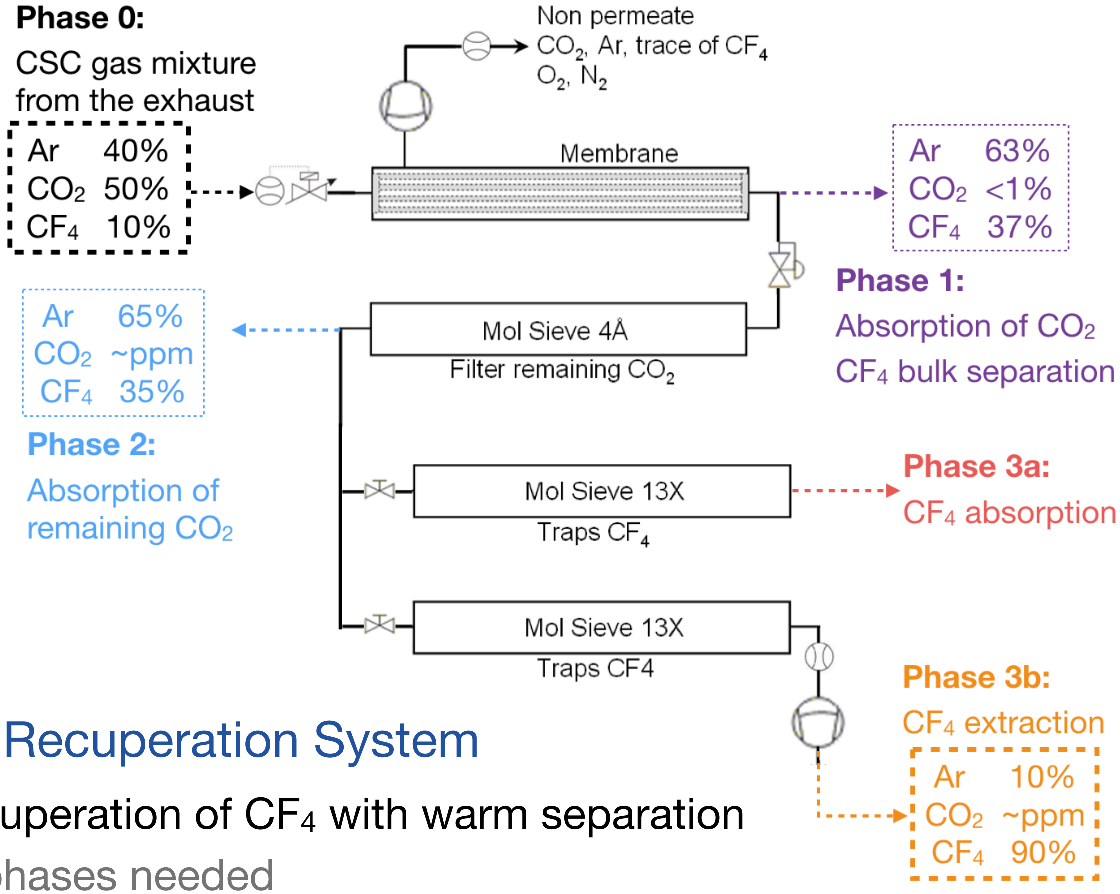
Gas recuperation: CMS CSC CF_4

CSC Gas System

- Detector volume ~90 m^3
- Gas mixture: 50% CO_2, 40% Ar, **10% CF_4**
- Gas recirculation: 90%
  - No possibile to increase due to detector permeability to Air
- ~600 l/h at exhaust -> 60 l/h of CF_4



GHG reduction from Run1 to Run2 up to **45%**



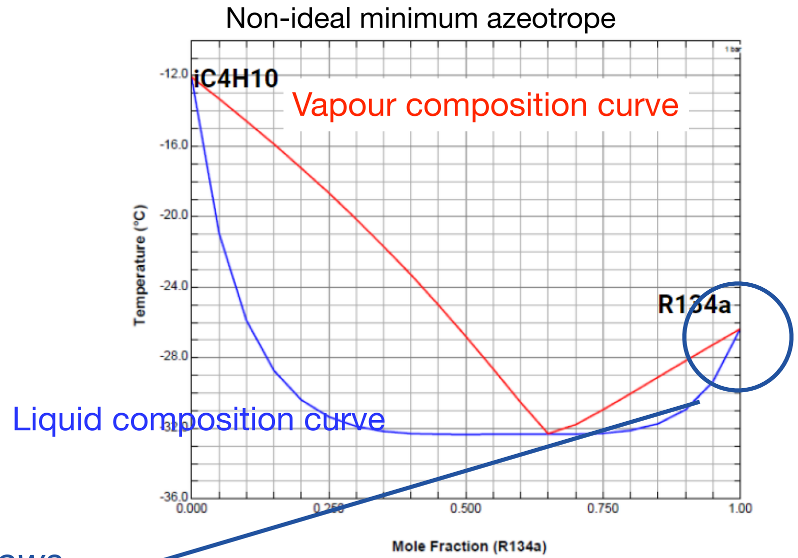
CSC Recuperation System

- Recuperation of CF_4 with warm separation
  - 3 phases needed
- Current recuperation efficiency ~70%
  - Several parameters affect recuperation efficiency
- CF_4 quality satisfactory
  - Recuperated CF_4 quality to monitor
- CSC detectors operated with recuperated CF_4 during Run 2
  - No change in the CSC performance observed

Gas Recuperation: $C_2H_2F_4$ for RPC detectors

ATLAS and CMS RPC Gas Systems

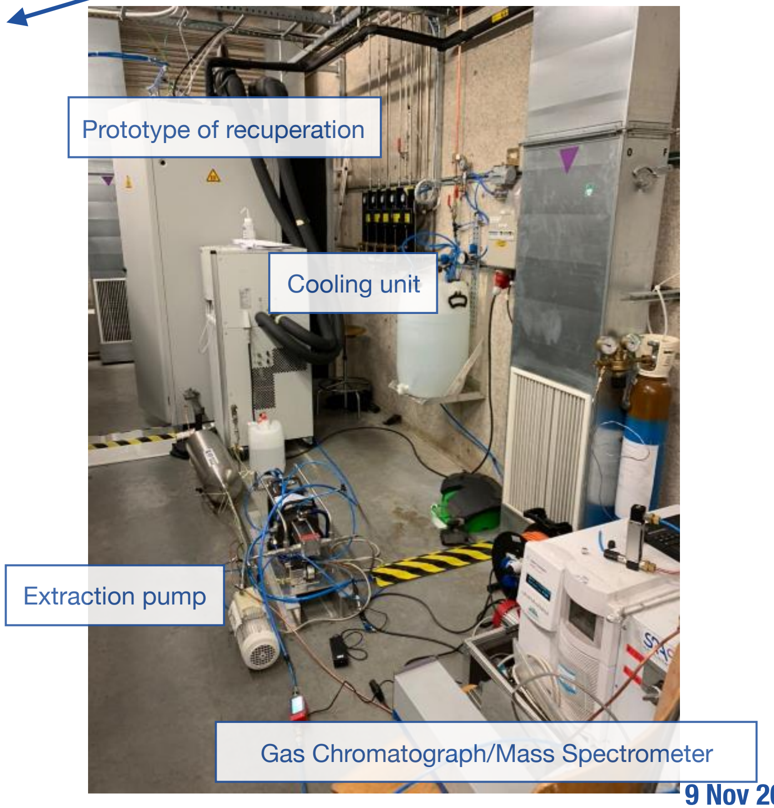
- Detector volume ~15 m^3
- Gas mixture: ~95% **$C_2H_2F_4$**, ~5% iC_4H_{10}, 0.3% **SF_6**
- Gas recirculation: ~90%
  - maximum recirculation validated for RPC detectors
- Fundamental to repair detector leaks
  - To have the gas at the exhaust (600-1000 l/h)



Slow heating of the liquified azeotrope allows to enrich the liquid of R134a and the vapour of iC_4H_{10}, obtaining the separation

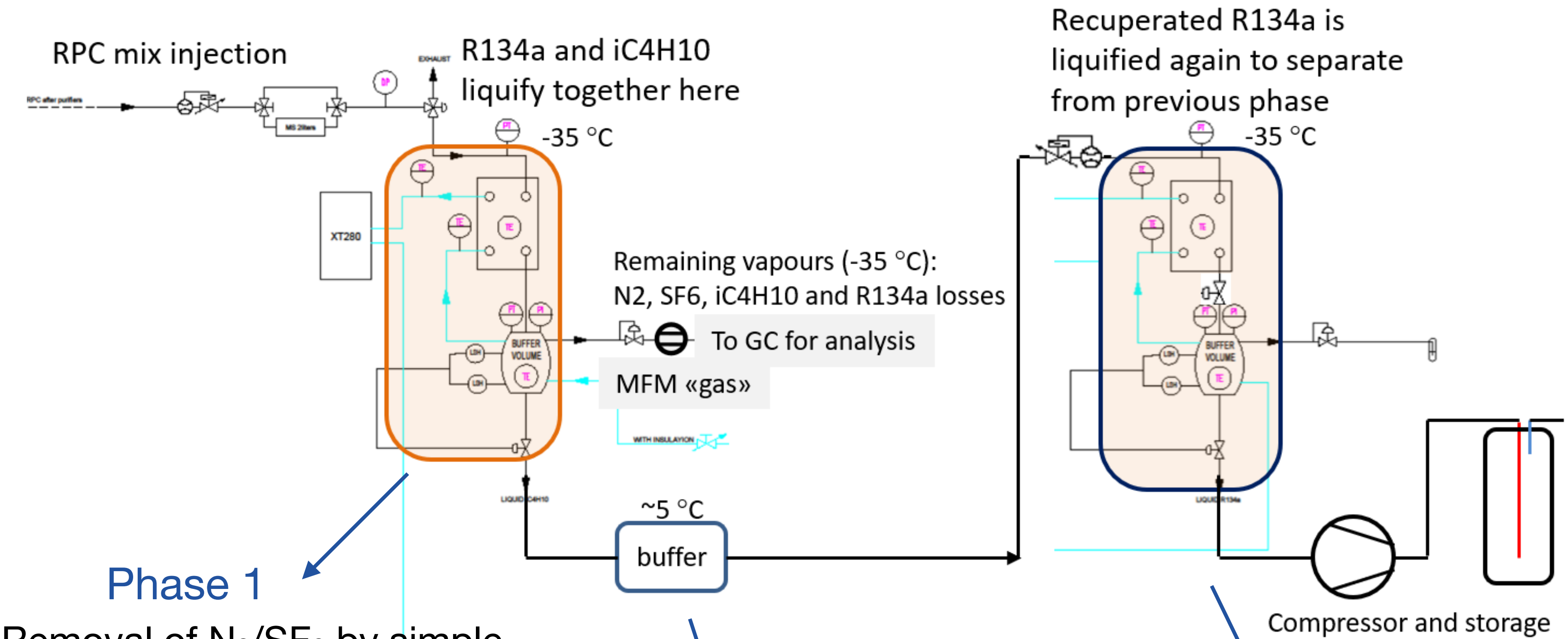
RPC Recuperation System

- Not convenient to recuperate the gas mixture
- Cold separation for R134a
  - Thermodynamic phase transitions
- R134a and iC_4H_{10} form an azeotrope
  - A mixture of liquids whose proportions cannot be altered or changed by simple distillation
  - Intramolecular force of same-species is much higher than the reciprocal attraction separation by quasi-static increase of temperature



Gas Recuperation: $C_2H_2F_4$ for RPC detectors

New $C_2H_2F_4$ recuperation prototype under study/test since 2019



Phase 1

- Removal of N_2/SF_6 by simple distillation
  - Gas mixture in buffer 1 cools down at -35 °C
  - N_2/SF_6 in vapour phase

Phase 2

- Detachment of R134a from iC_4H_{10}
  - Liquid heats up and vapour is made of azeotrope
  - Vapours go back in buffer 1
  - Liquid R134a go in buffer 2

Phase 3

- Compression of R134a
  - Vapour is compressed in liquid storage

Recuperation efficiency ~80%

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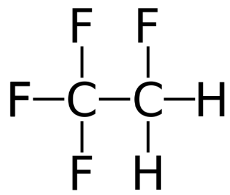
Possible alternatives to $C_2H_2F_4$ and SF_6

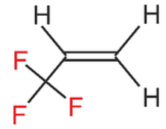
New eco-friendly liquids/gases have been developed for industry
as refrigerants and HV insulating medium… not straightforward for detector operation

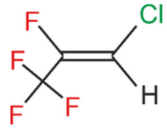


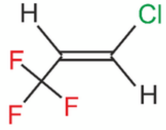
R134a
($C_2H_2F_4$)
GWP 1430

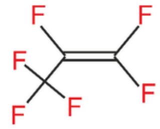
Hydro-Fluoro-Olefin (HFO)
C=C double bond
fluorine-containing
hydrogen-containing

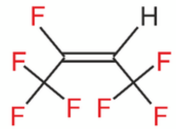
GWP <10

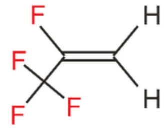

HFO-1243zf

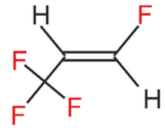

HCFO-1224yd

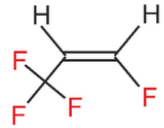

HCFO-1233zd

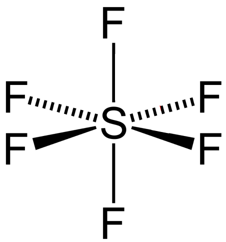

HFO-1216


HFO-1336mzz(Z)

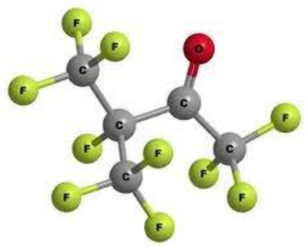

HFO-1234yf


HFO-1234ze(E)

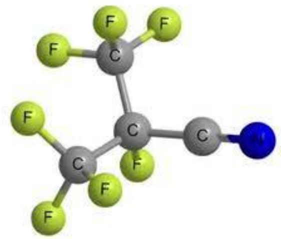

HFO-1234ze(Z)



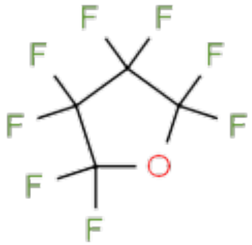
SF_6
GWP 23900



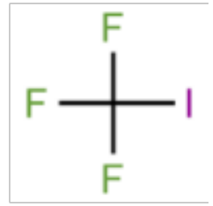
3M™ Novec™ 5110
($CF_3C(O)CF(CF_3)_2$)
GWP <1



3M™ Novec™ 4710
($(CF_3)_2CFCN$)
GWP 2100



C_4F_8O
GWP 8700



CF_3I
GWP <1

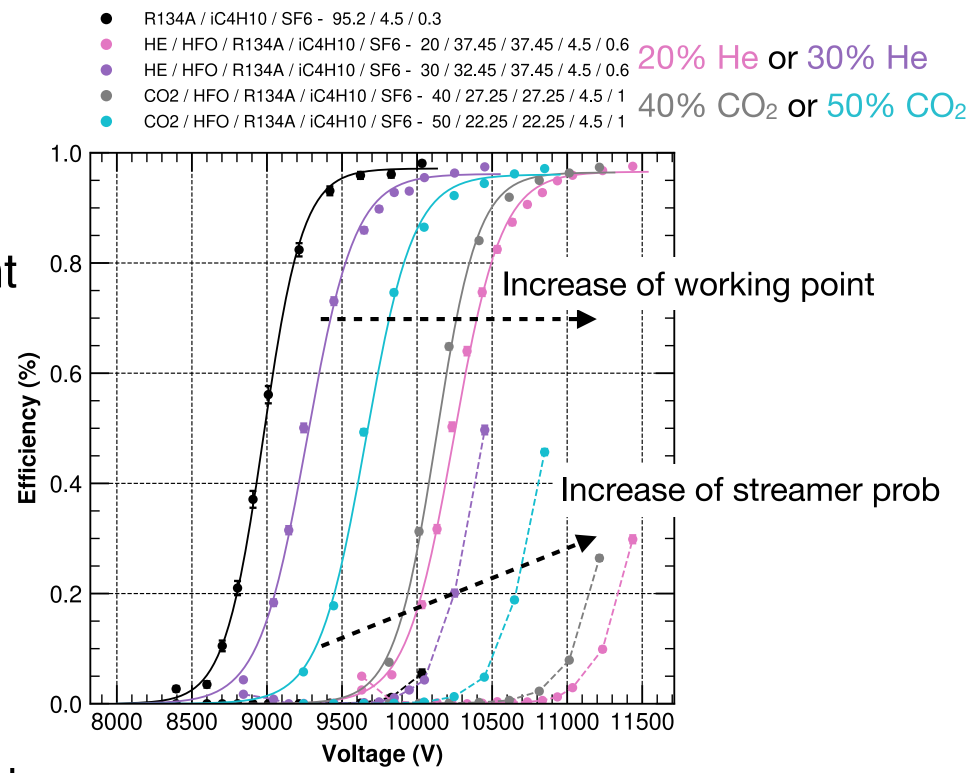
The goal is to find eco-friendly gas mixtures
that are compatible with the current RPC detector systems
(i.e. no change in HV cables, FEB electronics, gas system, etc.)

Mini-workshop on gas transport parameters for present and future generation of experiments
https://indico.cern.ch/event/1022051/overview

Results with eco-friendly gas mixtures for RPC

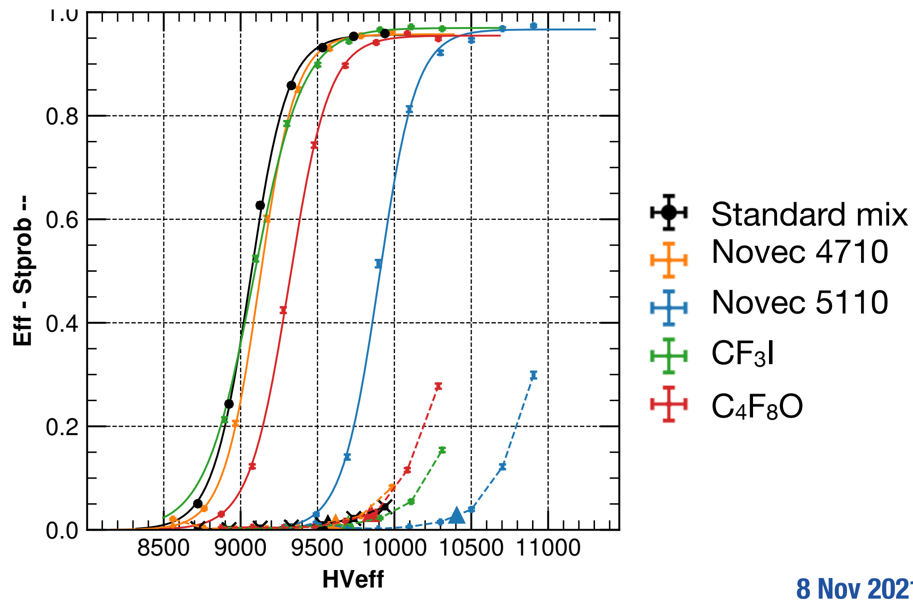
HFO as substitute of $C_2H_2F_4$

- HFO cannot directly replace $C_2H_2F_4$
  - Very high applied voltage
  - more streamers
- Addition of He or CO_2 to lower the working point
  - between 20% and 50% but increase of streamers
  - need to increase SF_6 concentration
- Use both HFO and $C_2H_2F_4$ in same mix
  - HFO reduces the GWP
  - $C_2H_2F_4$ reduces the signal charge
- More than 50 eco-friendly gas mixtures tested



Substitutes of SF_6

- Novec alternatives to SF_6 for arc quenching and insulation applications
  - Dielectric breakdown strength ~1.4-2 times > SF_6
- Novec 5110
  - Discrete performance but… it breaks with UV light
- Novec 4710
  - Very good performance but… it reacts with H_2O
- CF_3I
  - Very good performance but… toxic and mutagenic
- C_4F_8O
  - Good performance but…not low GWP

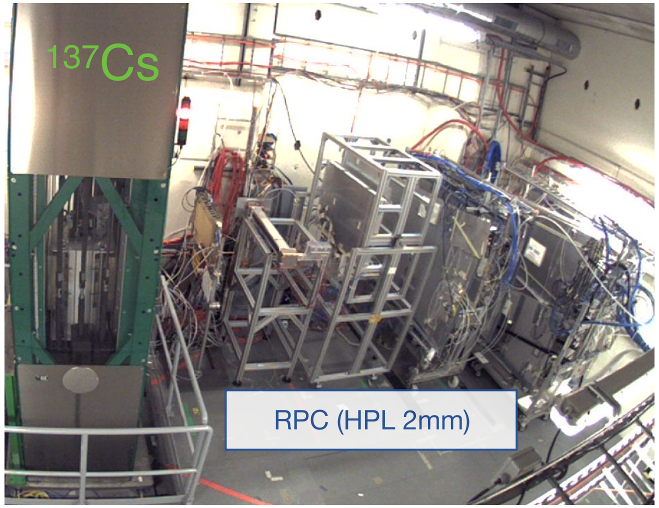


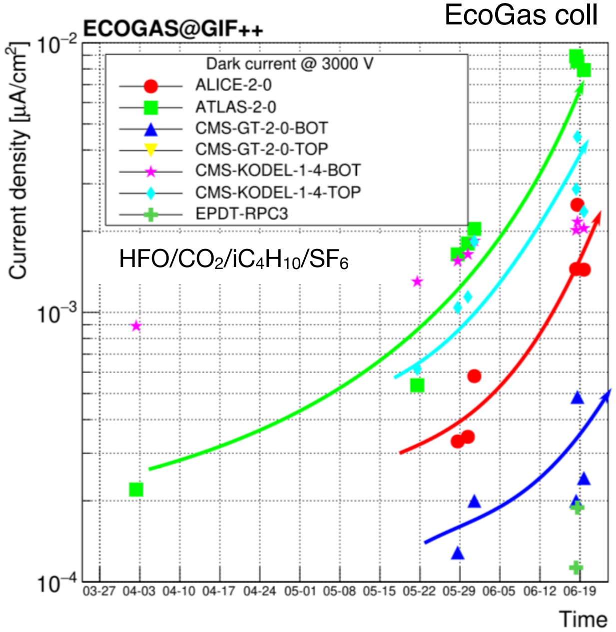
Long-term studies with HFO gas mixtures

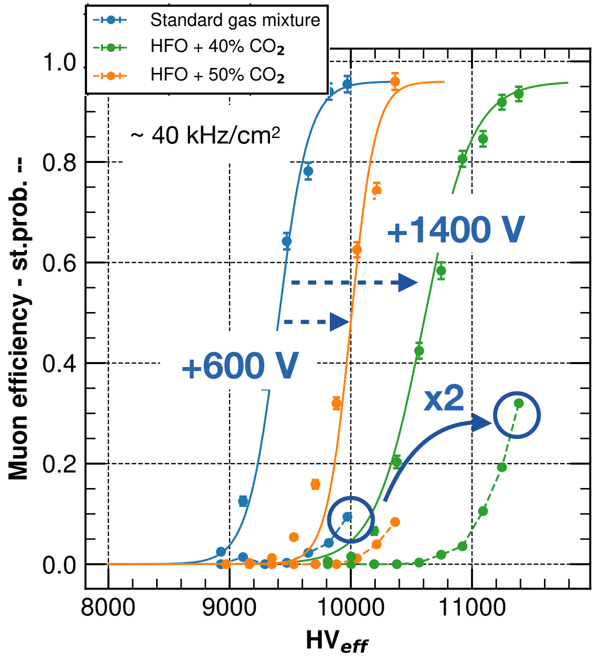
Performance studies of several eco-friendly gas mixtures for RPCs operated at different background conditions

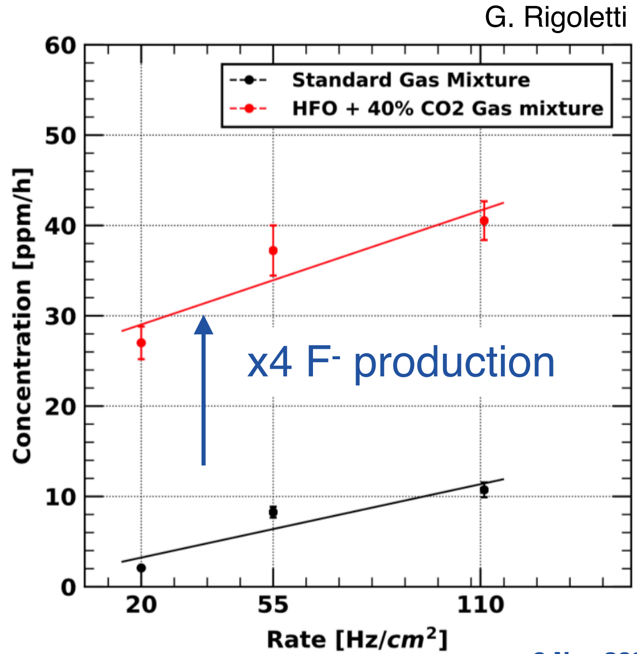
EcoGas collaboration

- GIF++: 12.2 TBq ^{137}Cs + H4 SPS beam line
- Long-term studies (aging-test)
  - Fundamental for the validation of new eco-friendly gas mixtures. Accumulation of high integrated charge
- Studies on detector performance
  - In presence of LHC and HL-LHC like background radiation
- Studies on creation of impurities
  - HFO breaks easier than $C_2H_2F_4$ during detector operation









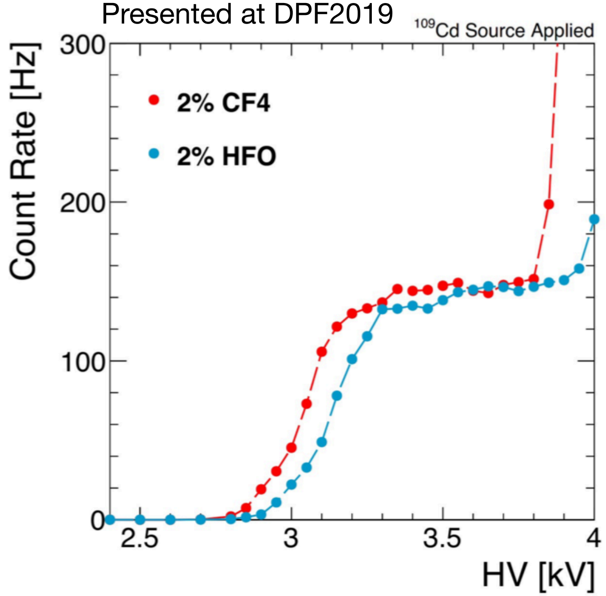
Possible CF_4 replacements

CF_4 is used in different types of particle detectors to prevent aging, to enhance time resolution or because of its scintillation photon emission

CMS CSC studies

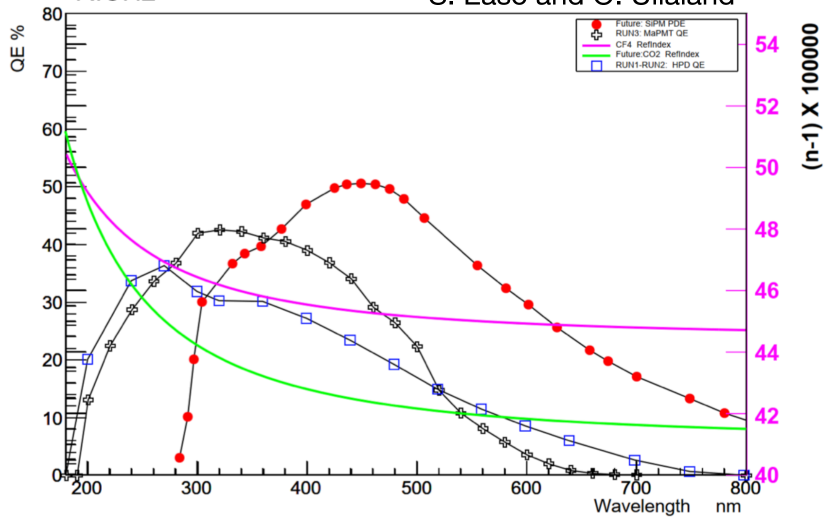
- CF$_4$ is a source of fluorine radicals to protect against anode ageing
  - Now 10% CF_4 in CSC gas mixture
- Two possibile approaches to reduce GHG consumption (beyond the recirculation and recuperation systems)
  - Decrease the CF_4 concentration: preliminary results show that 5% could be safe for operation
  - Look for alternatives to CF_4 :tried CF_3I and HFO1234ze
  - Several other gas candidates are considered for investigation

Presented at DPF2019



LHCb RICH studies

- RICH detectors use either CF_4 or C_4F_{10}
  - Necessary for good refractive index
- Replacement of C_4F_{10} with C_4H_{10}
  - Refractive index matches very well
  - But C_4H_{10} flammable
- Replacement of CF_4 with CO_2
  - Under investigation
- Use of SiPM to reduce the chromatic error and increase the yield



Why it is so difficult to find good GHG alternatives

When looking for alternatives eco-friendly gases, several factors have to be taken into account

Safety

Safety first for detector operations

- Gas mixture not flammable
- Gas components cannot have high toxicity levels

Tradeoff between flammability and GWP

- Replacing F with Cl or H: it shortens atmospheric lifetime BUT increase flammability limit
- Adding C=C bound: it increases reaction with O_2

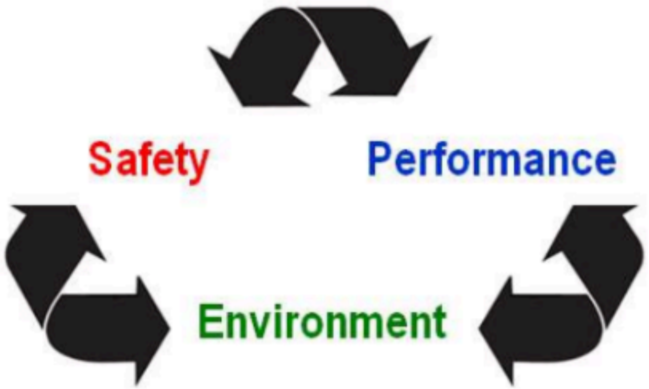
Performance

GWP is related to IR absorption over time. Low GWP gases have short atmospheric lifetimes

- Water solubility —> rain out
- OH reactivity —> oxidation
- UV absorbance —> photolysis

RPC short and long term performance are affected

- Good quenching gases required
- Radiation-hard gas required
- Gases cannot heavily react with H_2O or UV radiation



Environment

GWP represents the main environment concern

Conclusions

With climate change a growing concern,
CERN is committed to reduce its direct greenhouse gas emissions

Optimization of current technologies

- Gas recirculation systems are the best way to reduce GHG consumption
- Nowadays upgrades of gas systems beyond original design

Gas recuperation plants

- Used when not possible to recirculate 100% of the gas
- Very complex and different technologies depending on the GHG to recuperate

Alternative gases

- A lot of work especially in RPC community to search for alternative to $C_2H_2F_4$
- Not an easy task to find new eco-friendly gas mixture for current detectors

GHG Disposal

- Very last alternative: only if previous strategies will not work

Back-up slides

Gas Systems at the LHC experiments

The gas systems are complex apparatus
that extend over several hundred meters and have to ensure an extremely high reliability
*in terms of **stability** and **quality** of the gas mixture delivered to the detectors*

At LHC Experiments we have 30 gas systems for a total of ~300 modules interconnected with ~90 km of pipes and controlled/monitored with PLCs and > 1000 sensors

Reliability

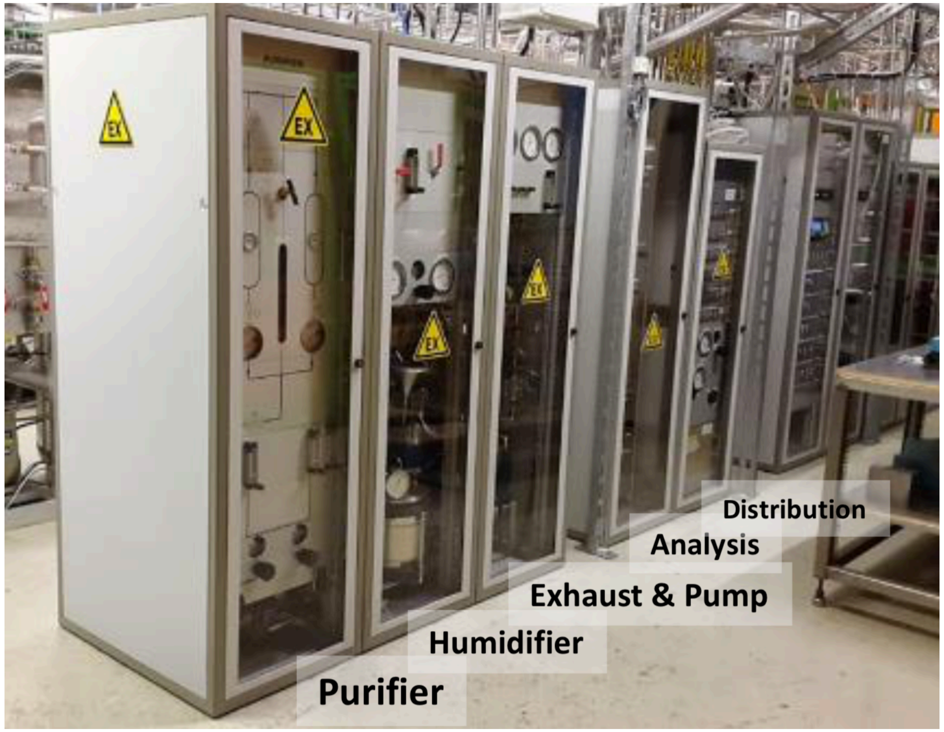
- LHC experiments are operational 24/24 7/7
- Gas systems must be available all time

Automation

- Large and complex infrastructure
- Resources for operation
- Repeatability of conditions

Stability

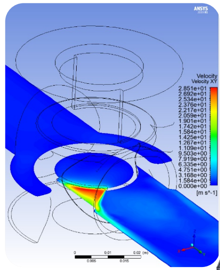
- Detector performance are strictly related with stable conditions (mixture composition, pressures, flows, ...)

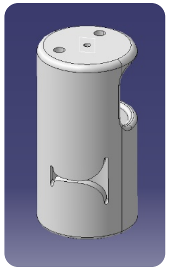


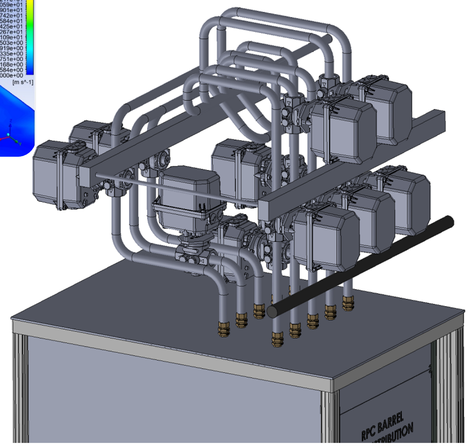
Optimization of distribution systems: CMS RPC

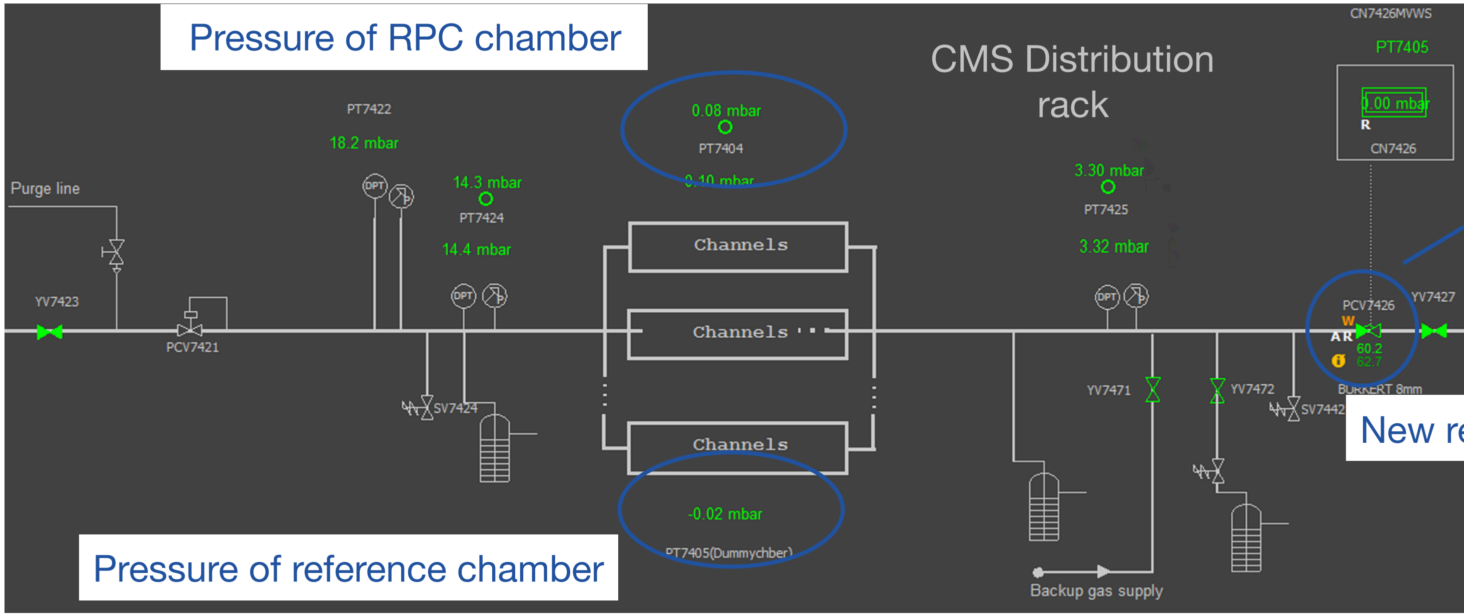
Goal: to try to minimise as much as possible any fluctuation of pressure and flow at the detector level

- New automated regulation valves on the return of each distribution rack to minimize any pressure changes
  - To decrease the risk of developing new leaks at the detector level
- 30 distribution racks for Barrel and Endcap divided into top and bottom
  - Different valve seats depending on pressure, flow, etc.
- Installation of 30 reference volumes
  - To have a good reference for the regulation of the detectors pressure





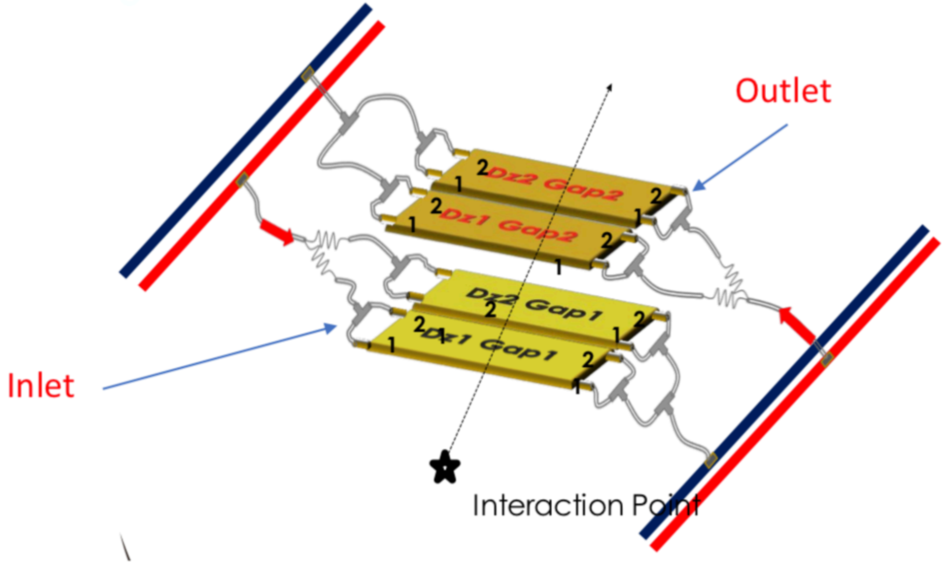




Causes of the leak: ATLAS case

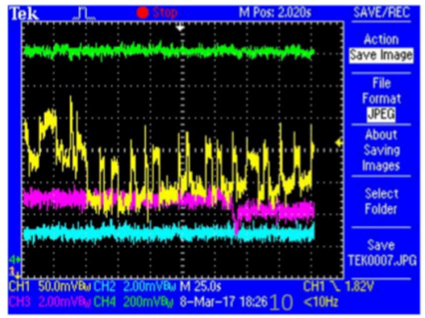
The ATLAS RPC leaks are **concentrated in the gas inlets and outlets.**

Typical new cracked inlet



The following main causes were individuated:

- A lower than expected quality in the original polycarbonate moulded inlet and outlet production
- A stress applied to the gas inlets through the gas pipes
- The gas system is generating a constant stress in form of fast propagating flow changes (order of 1-2 %)
- The former purge procedure (happening at each YETS) was producing a very large shock with a consequent large system damage.



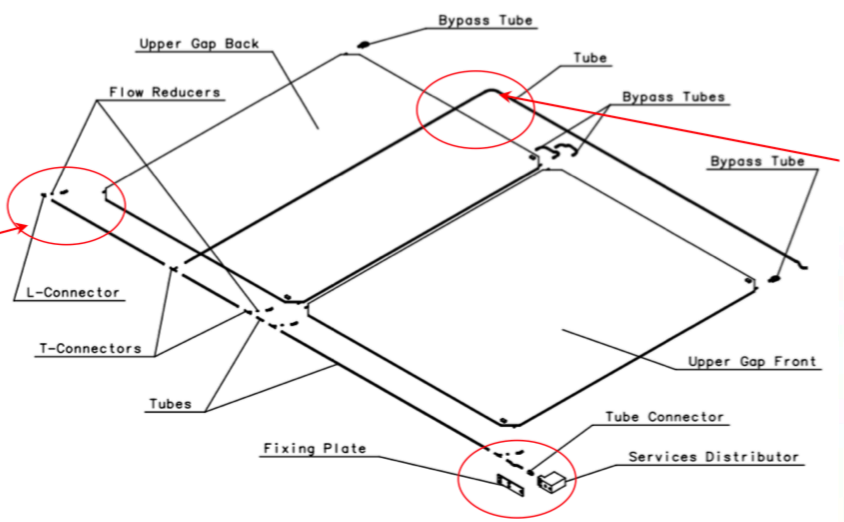
G. Pugliese: https://indico.cern.ch/event/1022051/contributions/4325945/attachments/2231022/3780366/CMS_ATLAS_talk_22_4_21.pdf

Causes of the leak: CMS case

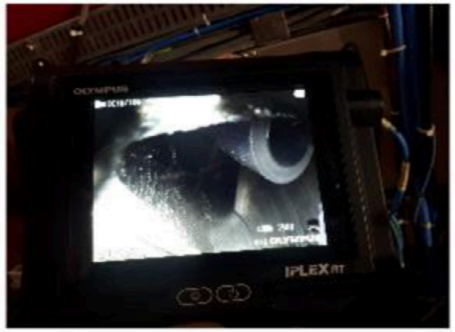
The CMS RPC leaks are mainly caused by:

1. T or L polycarbonate gas connectors break due to too much stress applied through the gas pipes.
2. Polyethylene LD pipes brittle/deteriorated or cut. This problem is mainly present in the last two station where two chambers are internally connected in parallel.
   - One "bad" batch of pipes was identified. Cracked pipes are all coming from the same batch.
   - Environmental cavern Humidity can accelerate this process.

Broken L



Cut bypass pipe RB3/RB4



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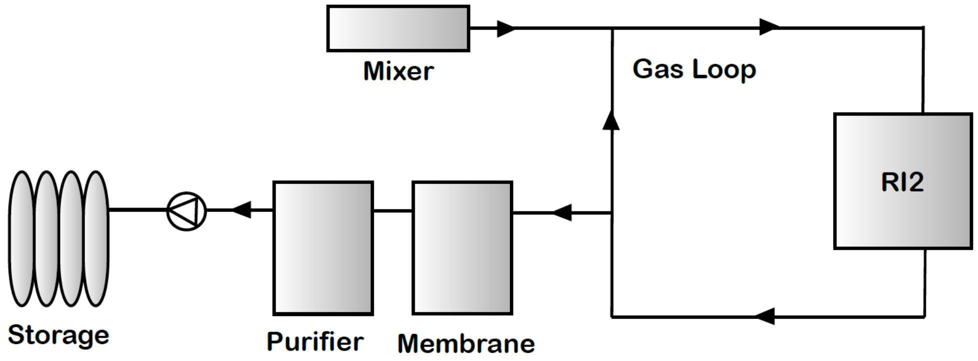
Gas recuperation: LHCb RICH2 CF_4

RICH2 Gas System

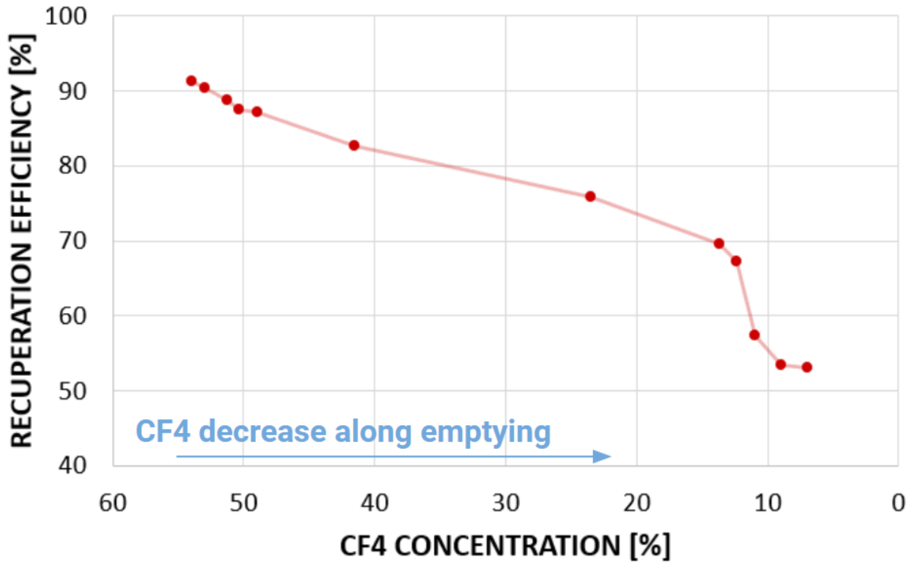
- Detector volume ~100 m^3
- Gas mixture: **92% CF_4**, 8% CO_2
- Gas recirculation: ~100%
  - Small quantity lost in leaks or for gas system operation

GHG reduction from Run1 to Run2 up to **60%**



RICH2 Recuperation System

- Two recuperation modes (warm separation)
  - During long shutdown: emptying detector
  - During Run: recuperation of small quantities otherwise lost in gas modules
- New system implemented in LS2
  - Upgrades on-going



Performance

- Recuperation efficiency ~60%
- About 30 m^3 of CF_4 recuperated in LS2
- CF_4 quality satisfactory
- CF_4 recuperated will be re-used for Run 3 operation

Gas disposal

Abatement plants are employed when GHGs are polluted and therefore are not reusable

In case all studies on recuperation will not bring to efficient recuperation plants, industrial system able to destroy GHGs avoiding their emission into the atmosphere have been considered

Quite heavy infrastructure required:

- CH_4/city gas + O_2 supply + N_2 supply
- Waste water treatment
- PFC/HFC are converted in CO_2 + HF acid dissolved in water
- disposal of remaining waste/mud
  - To have the gas at the exhaust (600-1000 l/h)

Joint CMS and EP-DT gas team is studying the feasibility

Found also companies available to take PFC/HFC based mixture for disposal: but extremely expensive

Possible SF_6 replacements

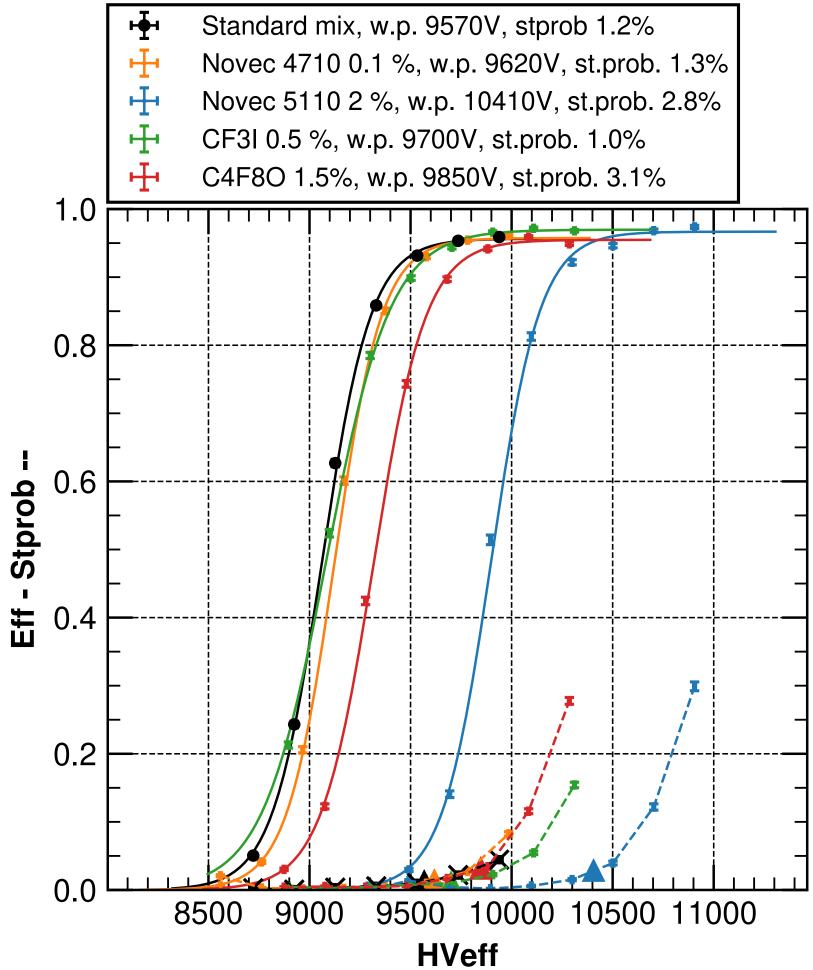
SF_6 has a very high GWP and it contributes for ~5% in the GWP of RPC gas mixture

3M™ Novec™ Dielectric fluids

- Very good alternative to SF_6 for arc quenching and insulation applications
  - Developed few years ago
  - Dielectric breakdown strength approximately 1.4-2 times that of SF_6
  - Especially used in HV industrial plants
- Novec 4710 (GWP 2100)
  - Very good performance but…
  - It may react with water
- Novec 5110 (GWP <1)
  - Very low GWP but..
  - RPC performance not optimal
  - sensitive to UV radiation

Other alternatives

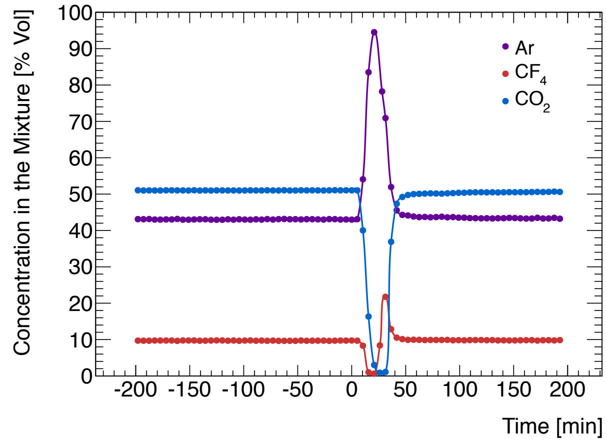
- Looks for other gases not used only for HV plants
  - Other electronegative gases could work
- CF_3I (GWP 0.4)
  - Good performance but…
  - Toxic, mutagenic, ODP 0.008
- C_4F_8O (GWP ~8000)
  - Good performance at 1.5%
  - 1.5% C_4F_8O GWP equivalent to 0.5% SF_6

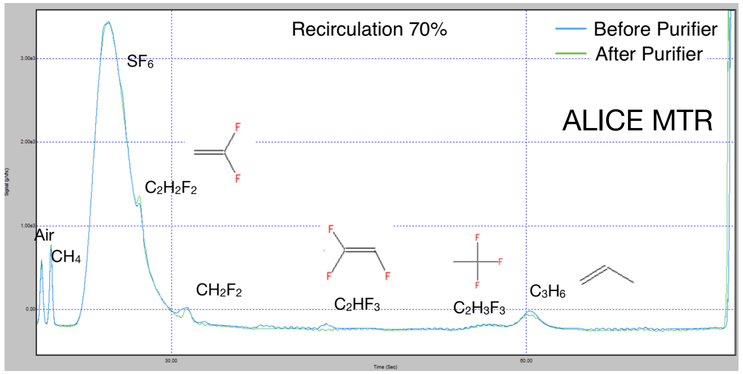


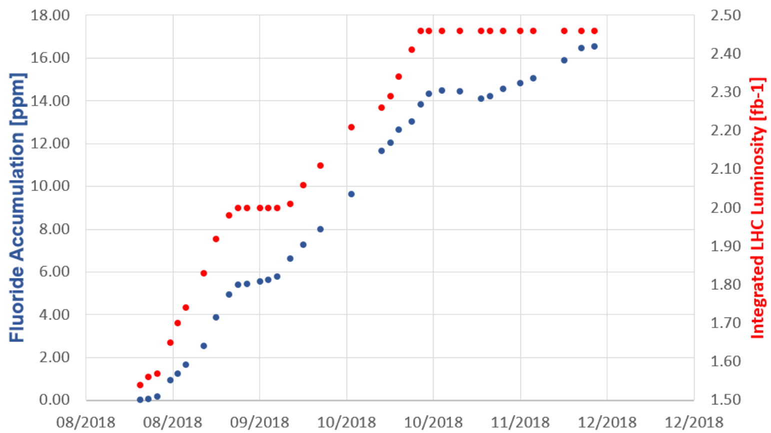
Gas recirculation systems: complexity

- Gas recirculation system is more complex
  - Pressure and flow fluctuations, etc
- Creation of impurities
  - They could accumulate in the gas system
  - Their concentration depends on luminosity and recirculation fraction
  - They could affect long-term detector operation
- Compulsory use of cleaning agents
  - Needed to absorb impurities
  - Destabilisation of gas mixture composition

Purifier: destabilisation of gas mixture







ALICE MTR

Gas mixture: 89.7% $\mathbf{C_2H_2F_4}$, 10% iC_4H_{10}, 0.3% $\mathbf{SF_6}$

GHG reduction from Run1 to Run2 up to **75%**

- Several studies needed to allow increase of recirculation fraction

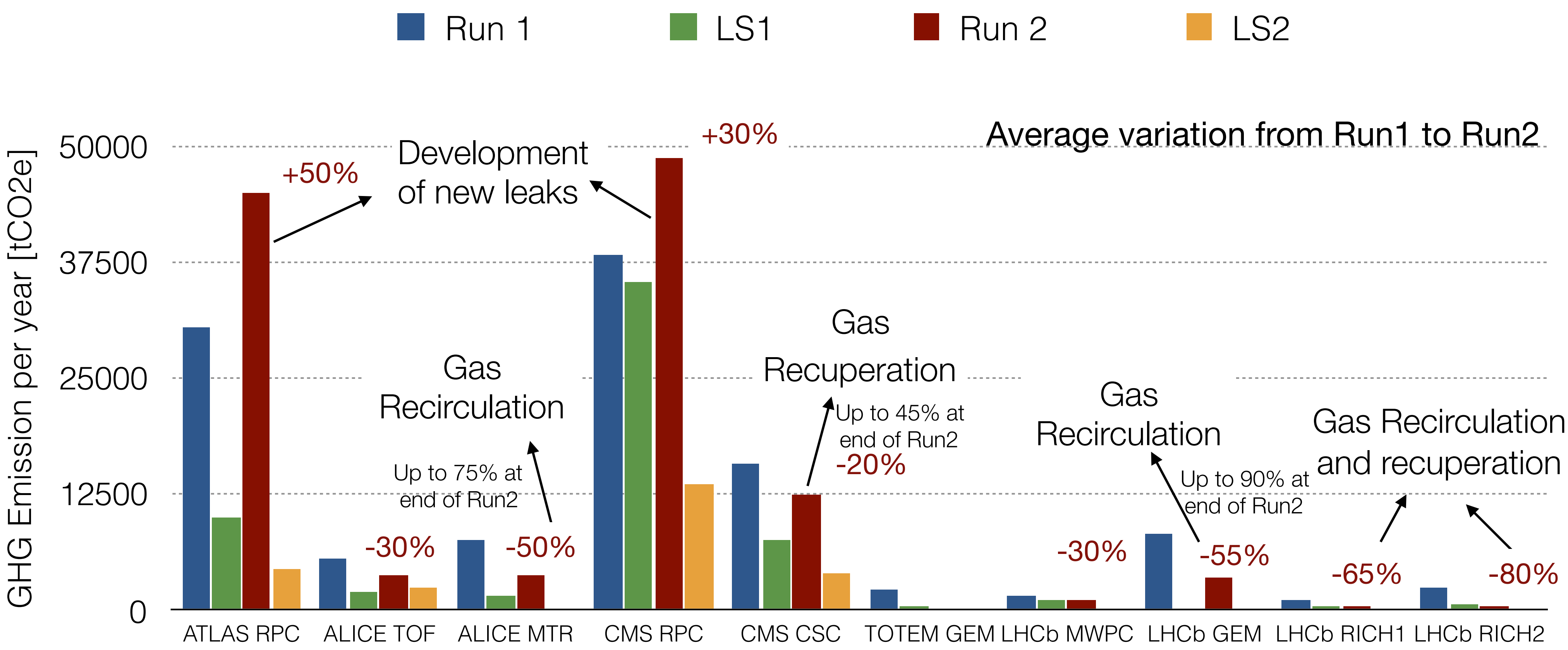
LHCb GEM

Gas mixture: 45% Ar, 40% $\mathbf{CF_4}$, 15% CO_2

GHG reduction from Run1 to Run2 up to **90%**

- Dedicated R&D needed as it was the first time GEM were operated in gas recirculation

GHGs for particle detection at LHC: Run1 vs Run2



- From Run1 to Run2 only increase of emissions is ATLAS and CMS RPC due to development of new leaks at detector level
- All other detector systems had a decrease of GHG emission from -20% to 80%
  - Thanks to the different gas system upgrades performed and a major attention on GHG use